Development of a Novel Coupled Simulation Tool to Study Ocean-Estuary Exchange

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LONG-TERM GOALS

The long-term goal of this project is to develop a coupled ocean-estuary simulation tool that will consist of the Regional Oceanic Modeling System (ROMS) and the nonhydrostatic, unstructured-grid SUNTANS model, in order to study the interaction of coastal regions with estuaries. The scientific goal will be to understand the dynamics of ocean-estuary exchange between San Francisco Bay and the coastal Pacific Ocean, with ROMS simulating the coastal Pacific Ocean, and SUNTANS simulating San Francisco Bay.

OBJECTIVES

The primary objective of this project is to develop and implement a coupled hydrodynamics and sediment-transport simulation tool to study the complex three-dimensional, coupled ocean-estuary processes that influence exchange through the Golden Gate channel in San Francisco Bay. In order to understand the influence of regional processes in the coastal ocean and how they are coupled to local processes in San Francisco Bay, the project will employ a one-way coupled simulation tool, in which a model for San Francisco Bay is coupled to a regional model for the coastal Pacific Ocean. The SUNTANS model (Fringer et al., 2006a) will be employed to simulate flow in San Francisco Bay, and it will obtain boundary conditions at the coastal ocean from simulations of the California coastal current using ROMS (Shchepetkin and McWilliams, 2005). SUNTANS is well-suited to simulate the exchange flow at the Golden Gate because it employs an unstructured grid, which enables simulation domains that include the entire Bay while also resolving finescale flow features near the Golden Gate. Furthermore, because SUNTANS is a nonhydrostatic code, it will capture nonhydrostatic features of the exchange flow which may be important at high resolution. ROMS, on the other hand, was originally written to simulate regional flows like the California Coastal Current, and employs highly accurate methods to simulate the complex dynamics of upwelling fronts, jets, and squirts over seasonal time scales (Marchesiello, et al., 2003). Using a stand-alone SUNTANS, simulations will be performed in idealized domains to understand the fundamental mechanisms governing three-dimensional exchange. In the real, field-scale domain, one-way coupling will be used to understand how tidal and seasonal variability in the coastal currents as well as in the Bay influence the dynamics of ocean-estuary exchange through the Golden Gate channel.

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APPROACH

Simulations of San Francisco Bay will employ SUNTANS (Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator), a free-surface, nonhydrostatic, unstructured-grid, parallel coastal ocean and estuary simulation tool that solves the Navier-Stokes equations under the Boussinesq approximation (Fringer et al.,2006a). The formulation is based on the method outlined by Casulli & Walters (2000), in which the free-surface and vertical diffusion are discretized with the theta-method, which eliminates the Courant condition associated with fast free-surface waves and the elevated friction term associated with small vertical grid spacing at the free-surface and bottom boundary. For flows with extensive wetting and drying such as San Francisco Bay, advection of momentum is accomplished with the semi-Lagrangian advection scheme (Casulli and Cheng, 1992; Staniforth and Temperton, 1986), which ensures stability in the presence of cells that fill and empty with the tides.

To simulate the influence of coastal currents on exchange between San Francisco Bay and the coastal Pacific, the SUNTANS simulations will be nested within the ROMS model (Shchepetkin and McWilliams, 2005), which also has a nonhydrostatic module (Kanarska, et al., 2007). ROMS is discretized in horizontal curvilinear coordinates and has a generalized terrain-following vertical coordinate that is configured to enhance resolution near the sea surface, and the time-stepping algorithm is split-explicit.

The simulations will employ a one-way coupled ROMS-SUNTANS tool that has been developed and applied to simulate nonlinear internal tides on the Australian North West Shelf (Fringer et al., 2006b), and development of the associated two-way coupled tool is underway in collaboration with Prof. J. McWilliams at UCLA in order to study tide-current interactions in Monterey Bay as well as the South China Sea. The SUNTANS simulations will be one-way nested within simulations of the California Coastal Current (Marchesiello et al., 2003). These simulations will provide sea-surface height, velocity fields, and sediment, salinity and temperature at the offshore boundary for SUNTANS. Because the ROMS simulations of the coastal current are nontidal, tidal currents from the OTIS tidal model (Egbert et al., 1994) are included by adding them to the mesoscale currents provided by ROMS at the SUNTANS boundaries. In one-way nesting, the boundary conditions supplied by ROMS influence SUNTANS, yet it is assumed that the flowfield as computed by SUNTANS does not influence the ROMS simulation (see, e.g. Fringer et al., 2006c). The boundaries of the SUNTANS simulations will be placed in order to minimize their potential influence on the exchange plume as it evolves on the shelf offshore of the Golden Gate. As long as the plume that exits the SUNTANS boundary does not have the potential to reenter the Bay, then the boundary is far enough from the mouth of the Bay and one-way nesting is justified.

Because both SUNTANS and ROMS are well-established models and the one-way coupling framework has already been developed (Fringer et al., 2006b), a bulk of this project will focus on implementation of the models to understand detailed physics of ocean-estuary exchange. Yet while SUNTANS has successfully been applied to study an estuary with significant wetting and drying (Wang et al., 2008), advection of momentum in the presence of wetting and drying presents significant challenges when high grid resolution is employed. While accuracy of semi-Lagrangian advection schemes depends on the time-accuracy of the traceback as well as the spatial accuracy of the interpolation (Staniforth and Cote, 1991), typical implementations of semi-Lagrangian advection for

estuarine simulations with coarse resolution employ first-order accurate spatial interpolation (Casulli and Cattani, 1994) and ignore vertical advection of momentum (Zhao, 2007). While this does not incur problems when coarse resolution is employed, high-resolution requires implementation of vertical advection and higher-order interpolation in the presence of complex bathymetry. This is not a trivial task, since it is difficult to ensure stability in the implementation of higher-order interpolation schemes on unstructured, finite-volume grids, particularly with wetting and drying (Zhao, 2007). However, if the stencil is suitably chosen, stability can be ensured, as pointed out by Leonard (2002). In the proposed work we will explore stencils for the Lagrangian traceback that improve stability when second-order accurate interpolation is used.

WORK COMPLETED

We have developed a full-bay calibrated hydrodynamic model. Calibration work has focused on simulations using two grids, namely a coarse grid with a nominal resolution of 200 m (Figure 1) and a fine grid with a nominal resolution of 25 m (Figure 2). The coarse grid employs a "false" delta which consists of two rectangular domains, while the fine grid computes flow in a cursory version of the Delta. Although we do not focus on obtaining calibrated hydrodynamics in the Delta, implementation of a cursory Delta provides for more accurate behavior of the tidal dynamics in North Bay without requiring excessive tuning of a false delta which can take quite a bit of time particularly on a high-resolution grid.

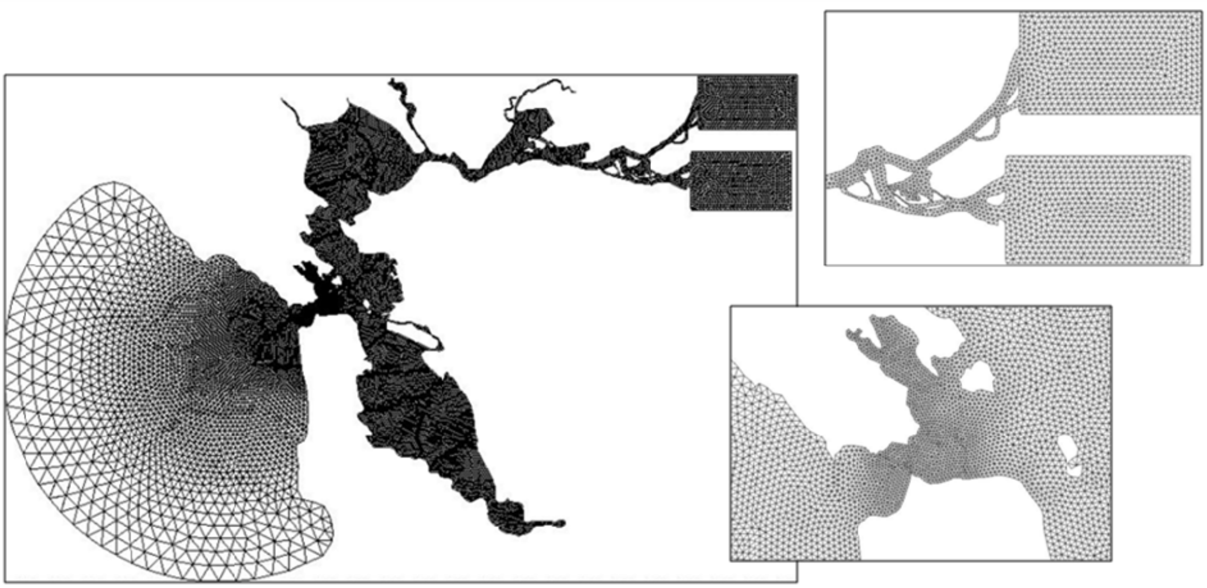


Figure 1: Coarse full-Bay grid with an average 200 m resolution throughout the Bay.

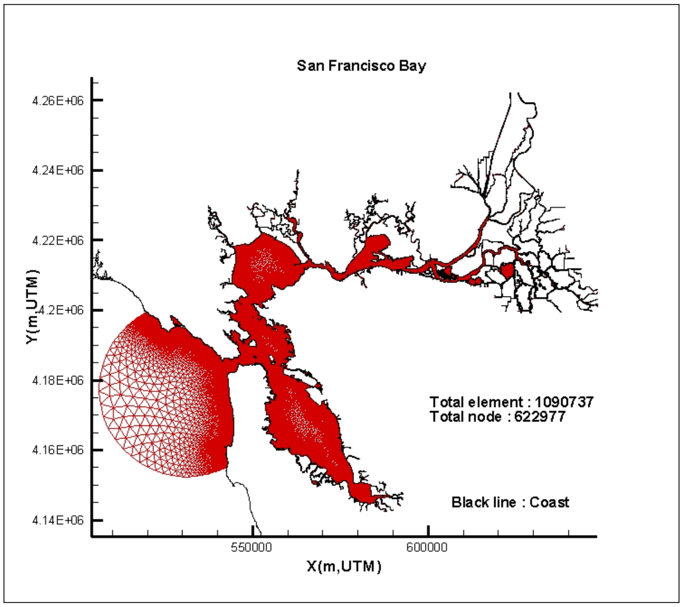


Figure 2: Fine full-bay grid with an average resolution of 25 m throughout the Bay.

The calibrated simulations using the coarse grid are employed over the 14-day period from 18 Jan 2005 to 31 Jan 2005. Tidal constituents from the NOAA buoy at Point Reyes are imposed at the ocean boundary, while freshwater inflow estimates from DAYFLOW[1] are imposed at the eastern-most boundaries of the false delta. The ocean salinity is fixed at 33.5 ppt over the simulation. Figures 3 and 4 show good agreement between observed and predicted tidal constituents at four points throughout the Bay, while Figures 5 and 6 show good agreement between observed and predicted top and bottom currents and salinity. Surface salinity maps have been created over the 14-day period, and several snapshots are depicted in Figure 7. More snapshots and a movie are available for viewing online at http://www.stanford.edu/~vchua/suntans-salinity.html.

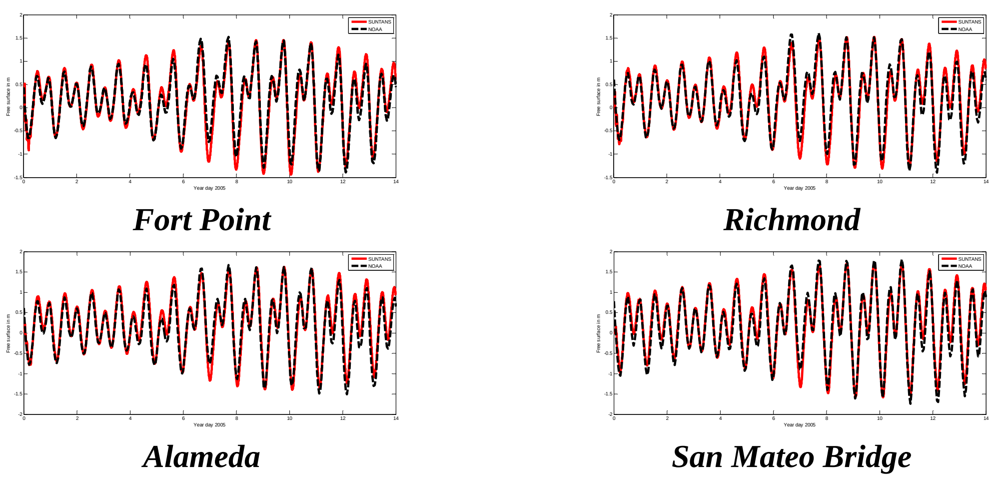


Figure 3: Comparison of predicted to observed free-surface height at four locations in San Francisco Bay. Red=predicted, Black=observed.

[1] http://iep.water.ca.gov/dayflow/output/index.html

Harmonic	Observed		Predicted		Error	
	Amplitude (cm)	Phase	Amplitude (cm)	Phase	Amplitude (cm)	Phase
M2	57.94	208.87	59.09	209.53	-1.15	-0.66
K1	43.70	234.17	50.92	234.83	-7.22	-0.66
O1	22.54	211.44	28.00	210.51	-5.46	0.93
S2	11.77	236.23	10.48	237.98	1.29	-1.75
N2	14.42	183.12	12.43	184.99	1.99	-1.87
Q1	4.04	200.21	4.53	201.81	-0.49	-1.60

Fort Point

Harmonic	Observed		Predicted		Error	
	Amplitude (cm)	Phase	Amplitude (cm)	Phase	Amplitude (cm)	Phase
M2	62.65	222.97	61.75	228.03	0.90	-5.06
K1	43.56	241.51	49.31	244.50	-5.75	-2.99
O1	22.05	220.69	26.42	222.06	-4.37	-1.37
S2	12.35	252.01	11.05	263.95	1.30	-11.91
N2	15.14	197.71	12.79	204.76	2.35	-7.05
Q1	3.70	212.64	4.31	214.71	-0.61	-2.07

Richmond

Harmonics	Observed		Predicted		Error	
	Amplitude (cm)	Phase	Amplitude (cm)	Phase	Amplitude (cm)	Phase
M2	69.71	223.78	68.30	229.34	1.41	-5.56
K1	45.04	241.80	50.50	245.77	-5.46	-3.97
O1	23.07	219.21	26.87	224.38	-3.80	-5.17
S2	13.85	255.30	12.51	267.40	1.34	-12.1
N2	16.63	199.07	14.07	206.82	2.56	-7.12
Q1	4.00	210.98	4.42	217.64	-0.42	-6.66

Alameda

Harmonic	Observed		Predicted		Error	
	Amplitude (cm)	Phase	Amplitude (cm)	Phase	Amplitude (cm)	Phase
M2	84.33	233.37	78.05	233.49	6.28	-0.12
K1	46.71	248.02	52.84	247.96	-6.13	0.06
O1	24.48	225.65	28.43	226.22	-3.95	-0.57
S2	16.60	274.15	14.84	275.29	1.76	-1.14
N2	19.37	210.79	15.98	211.80	3.39	-1.01
Q1	4.59	220.65	4.62	220.09	-0.03	0.56

San Mateo Bridge

Figure 4: Comparison of predicted to observed harmonic constituents at four locations in San Francisco Bay.

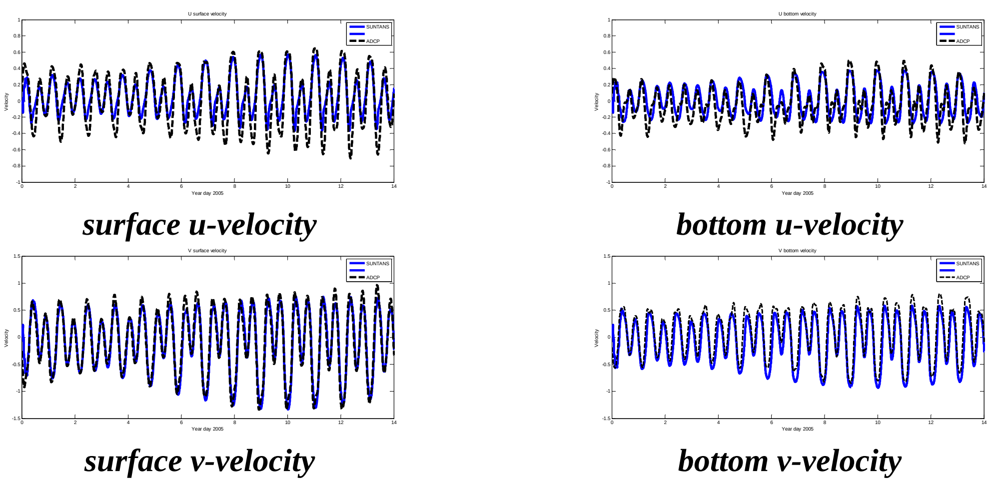
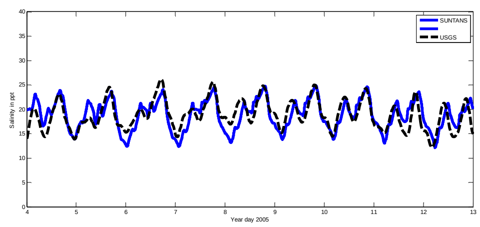
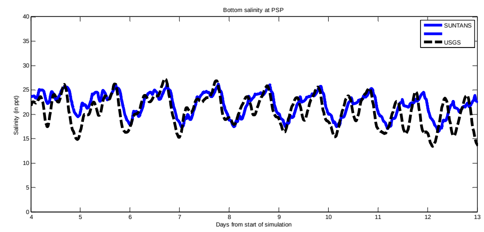


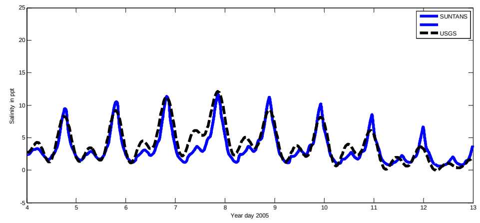
Figure 5: Comparison of predicted to observed top and bottom currents at Richmond. Blue=predicted, Black=observed.



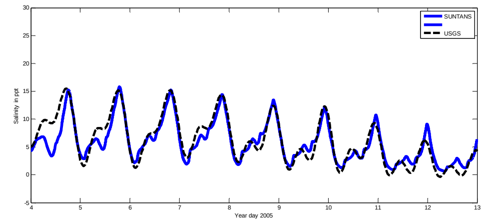
surface salinity at Point San Pablo



bottom salinity at Point San Pablo



surface salinity at Benicia



bottom salinity at Benicia

Figure 6: Comparison of predicted to observed top and bottom salinity at two locations in San Francisco Bay. Blue=predicted, black=observed.

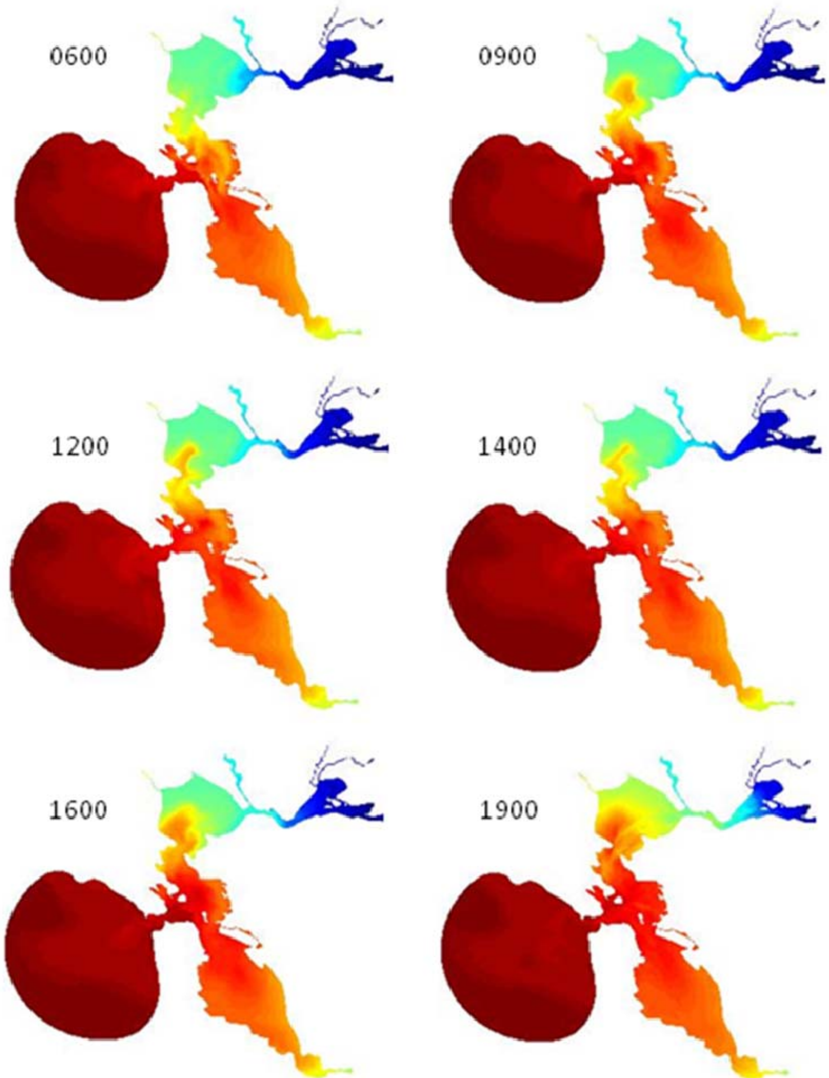


Figure 7: Surface salinity at six points in time during 26 Jan 2005. red=salty (32 ppt), blue=fresh.

IMPACT/APPLICATIONS

The coupled simulation tool that will be developed for this project has the potential to form the basis for a wide range of modeling studies of other important coupled ocean-estuary systems.

RELATED PROJECTS

The California Coastal Conservancy is fundin the development of an open-source hydrodynamics and sediment transport model using SUNTANS to assess the impacts of marsh restoration projects on salt and sediment dynamics in San Francisco Bay. Fringer is involved in this project in collaboration with Profs. Mark Stacey and Zack Powell at U. C. Berkeley and Profs. Jeffrey Koseff and Stephen Monismith at Stanford University.

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HONORS/AWARDS/PRIZES

Oliver B. Fringer, Presidential Early Career Award, 2009.